# Production Frontier Methods in Environmental Performance Measurement and Analysis

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# Production Frontier Methods in Environmental Performance Measurement and Analysis

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**ABSTRACT**

Performance measurement and analysis of firms and other production units is of great concern in many sectors of economy. Traditionally, performance measurement studies have ignored undesirable outputs such as air pollution, solid waste and water effluents, which are generated as by-products of the production process. However, from society's point of view, there are many compelling reasons to study how to abate emissions efficiently as well as to consider the benefits of the reduced emissions. As a response to this, a growing number of studies have concentrated on developing environmentally sensitive performance measures that explicitly account for emissions and credit a producer for reducing them. For measuring and analysing the environmental performance of firms, these studies employ so-called production frontier methods that are widely used in the field of performance measurement.

The objective of this thesis was to develop new quantitative approaches for environmental performance analysis based on the production frontier methods. The study consists of an introductory part and four articles, each of which contributes to the topic of environmental performance analysis from slightly different perspectives. The common theme for the new techniques proposed in the articles is that they utilize the ideas of the existing performance measurement techniques, but in comparison to the existing methods, also suggest some extensions that can be particularly useful in various kinds of environmental applications. The proposed approaches are based on the two most widely used production frontier methods: Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA). While Articles I-III develop new nonparametric approaches for environmental performance analysis based on DEA, Article IV concentrates on elaborating a new semiparametric stochastic frontier approach for technical and environmental efficiency measurement.

Although the main contribution of the study is methodological, empirical applications are also presented. We apply the developed approaches to the dynamic environmental performance analysis of 20 member states of European Union (Article I), eco-efficiency analysis of Sport Utility Vehicles in Finland (Article II) as well as to the environmentally adjusted performance evaluation of U.S. coal-fired electric power plants (Article IV). In addition, in Article III, we present a numerical example, where an environmentally conscious household considers investment in a new car.

**Key words**: production frontier methods, environmental performance, eco-efficiency, cost-benefit analysis, data envelopment analysis (DEA), stochastic frontier analysis (SFA)

# General Contents

# List of Original Articles

This thesis is based on the following articles, which are referred to by their Roman numerals I-IV:

I Kortelainen, Mika (2008): Dynamic Environmental Performance Analysis: A Malmquist Index Approach. *Ecological Economics* 64(4), 701-715. (© Copyright of Elsevier Science)

II Kortelainen, Mika and Timo Kuosmanen (2007): Eco-Efficiency Analysis of Consumer Durables Using Absolute Shadow Prices. *Journal of Productivity Analysis* 28(1-2), 57-69. (© Copyright of Kluwer Academic Publishers)

III Kuosmanen, Timo and Mika Kortelainen (2007): Valuing Environmental Factors in Cost-Benefit Analysis Using Data Envelopment Analysis. *Ecological Economics* 62(1), 56-65. (© Copyright of Elsevier Science)

IV Kortelainen, Mika (2008): Estimation of Semiparametric Stochastic Frontiers Under Shape Constraints with Application to Pollution Generating Technologies. MPRA Paper 9257, University Library of Munich, Germany.



**Contribution**

Mika Kortelainen is the sole author of Articles I and IV, while Articles II and III are based on joint work with Timo Kuosmanen. Kortelainen is the first author in Article II and the second author in Article III.

In Article II, the authors contributed equally to the development of the theoretical framework and empirical approach. The data collection and processing as well as the analysis have mainly been performed by Kortelainen. Both authors have contributed to the writing of the report.

The theoretical part of Article III was the result of inspiring discussions during Kortelainen's stay at the Wageningen University in the Netherlands in 2004. The formal analytical treatment is mainly due to Kuosmanen, but Kortelainen actively contributed to the development of the method. Both authors have contributed to the empirical application and writing of the report.

# Preface

The background of this doctoral dissertation dates back to summer 2003 when I was writing my Master's degree thesis. At that time Professor Timo Kuosmanen from Wageningen University (the Netherlands) was searching for a Ph.D. student for his research project "Measuring Eco-Efficiency Using Data Envelopment Analysis". I was very lucky to get recruited to this project, which belonged to the Third Phase of the Environmental Cluster Research Programme titled "Eco-Efficient Society", administered by the Ministry of the Environment in Finland. After finishing the Master's thesis in October, I started to work as a full-time researcher in the project. Since the topic was previously unfamiliar to me, I was quite unsure in the beginning whether I would be able to write a Ph.D. thesis related to this research field. Both the academic style and writing in English were also something that had to be learned step by step. However, after just three months of work, I already had some blueprints for the dissertation, and in February 2004, I started my Ph.D. studies at the University of Joensuu and in the Finnish Doctoral Programme in Economics.

During the two years I was working in the project (October 2003 – December 2005), I was able to put most of my time and effort on the courses required for Ph.D. and on writing the papers that now constitute the second and third article of the thesis. As a whole, the writing of these articles was a very educative and productive process. Although there are many reasons for this, the most important is the fact that I was privileged to write these papers jointly with my supervisor, Timo Kuosmanen. From the point of view of learning, another relevant experience that developed me as a researcher during this time was the refereeing process for these two papers. The writing of revisions and responses based on the referees' comments did not just improve the papers, but also strengthened my argumentation skills relevant to academics.

At the beginning of 2006, I was given a graduate school fellowship in the Finnish Doctoral Programme in Economics (FDPE) for which I am deeply grateful as it provided me with the financial support needed to carry out the research and provided me with some valuable contacts within the field. I continued working as a GS fellow in FDPE until May 2008, when I started in the post of a research associate in Aston Business School, Birmingham. In the course of the fellowship, I managed to write the first and fourth article as well as an introductory part to the thesis. Another aspect worth mentioning is my semester long research visit to Leonard N. Stern School of Business at New York University in fall 2006. During my stay at NYU, I benefited from the highly qualified guidance of my supervisor Professor Bill Greene, who is one of the world's most influential econometricians and probably best known for his popular econometrics textbooks. I want to thank him for making the visit possible, and FDPE, City of Joensuu and the Northern Karelia Fund of the Finnish Cultural Foundation for financial support.

In addition to my research visits to New York and Wageningen University (in 2004), I have had numerous opportunities to attend and present my work at international conferences and workshops. Thanks to the generous financial support from the Emil Aaltonen Foundation and Department of Economics and Business Administration at the University of Joensuu, I have been able to participate in 10 international conferences in 8 different countries as well as in 5 Finnish conferences and workshops. From different professional meetings,

especially the annual Productivity Workshops since 2004 in Toronto have been of great importance for my work. They have helped me keep up with the latest developments, and form invaluable contacts with overseas colleagues, among other benefits. In addition, from these conferences I have got new ideas and valuable feedback for which I am very thankful.

The person who I am most indebted to is my supervisor Timo Kuosmanen (MTT), who has shared his expertise with me during these past years. From the very beginning, he encouraged me to participate in international conferences and by doing this I got to understand the importance of presenting and marketing my own work. As a good example of Timo's influence, I presented my papers at 6 international conferences during the first two years of study! Furthermore, Timo has helped me in the process of writing papers of publishable standard by being a co-author in several papers and by commenting on the papers I have written myself. In short, he has been my guide into the academic world and besides that, a great mentor and a great friend. From Timo, I have also learned a lot about the importance of persistence and believing in your own ideas. For all of this, I stand in endless gratitude.

I also want to thank the second supervisor of my thesis, Professor Mika Linden (University of Joensuu). He has been a valuable advisor and supporter for me during my Ph.D. studies. In addition, Mika has been a knowledgeable discussant, and a major source of many excellent econometrics and statistics books. Mika's constructive critique has also improved many chapters of this work. I'm particularly grateful for his help with regard to the computations carried out for the last article of the thesis.

Furthermore, I am deeply grateful to Professor Peter Bogetoft (Copenhagen Business School) and Professor Kristiaan Kerstens (IÉSEG School of Management) for their role as the pre-examiners for this thesis. I want to thank them for their insightful comments and encouraging feedback. I am proud to have them both as the pre-examiners of my Ph.D. thesis and Kristiaan also as the opponent of the public examination.

I would also like to acknowledge two inspiring researchers, Dr Laurens Cherchye (Catholic University of Leuven) and Dr Timo Sipiläinen (MTT), with whom I have had the pleasure to work with during the past years. Both Laurens and Timo have also commented on some of the articles in the thesis and I am most thankful for their shared insights and look forward to working with them also in the future.

Lots of warm thoughts also go to my friends and colleagues at the department, who have had a major role in making my studies in Joensuu worthwhile. In particular, I am grateful to Tuukka Saarimaa for our numerous discussions and intense debates that have inspired me in various ways. Tuukka has also read through several versions of my papers and given comments that have helped to improve this work. I would also like to thank Tuomo Kainulainen, Mika Louhelainen, Jani Saastamoinen, Niko Suhonen and Sasu Tuominen for lunch hour and coffee break chats that have always cheered me up. From the faculty, I also want to mention and thank Dr. Matti Estola, since he was the first to encourage me to continue in Ph.D. studies when I was yet studying for the Master's degree. My appreciation also goes to Liisa Reichenvater, the secretary of the unit, and amanuenses Mari Kähkönen and Ulla Tolvanen, who have always kindly assisted me with all practicalities.

To my mother Irma, father Erkki and sister Sari and her children, Antti-Jussi and Matias, I am thankful for their love and confidence. They have given me a tremendous amount of support and always encouraged me to proceed in my studies. This journey would not have been possible without you.

Finally, my dearest thanks go to my wife, Minna, for her love and encouragement during this personal endeavor. Over the years, she has spent countless hours listening to my different considerations with regard to the thesis and has helped me in editing and refining the manuscript. She has also been there to remind me that there are other things in life more important than the Ph.D. research. Above all, she has been a party on this journey, and together we share the credit.

3 July 2008, in Birmingham, United Kingdom

*Mika Kortelainen*

# Introduction to the Articles

# Contents

# 1. Introduction

It is generally known that firms and other organizations operating in the same industry do not perform equally well. For example, some businesses are more profitable than their competitors, and some public organisations produce services more efficiently than others. Therefore, it is by no means surprising that performance measurement and analysis are of great interest in many sectors of economy. As evidence of this, there have been hundreds of studies measuring the performance of firms or other organizations in different industries, ranging from banking to electricity distribution, from education to postal services and from forestry to military, to name just a few.

Related to this field of research, the terms productivity and efficiency appear frequently in the media and are often used synonymously to each other. Although closely linked, they are yet two separate concepts. Productivity is technically defined as a ratio of outputs to inputs, while efficiency refers to the comparison of the observed and optimal value of productivity or other performance measure (such as cost or profit). This implies that in contrast to productivity, efficiency is regarded as a relative performance measure that depends on how one defines or measures the optimal level of performance. Importantly, there exists a great variety of different efficiency measures, such as technical efficiency, allocative efficiency and environmental efficiency, among others. Many of these have an important role in the field of productivity and efficiency analysis, which is a large and growing body of literature, consisting of several thousands of studies in the areas of applied economics, econometrics, operations research, and statistics (see e.g. Fried et al., 2008, for an introduction). This empirically oriented literature concentrates mainly on developing and applying various performance measurement techniques.

Traditionally, performance measurement studies have modeled production processes by assuming that firms produce only good outputs or that the produced outputs are freely disposable, which means that firms can decrease their outputs without additional costs. However, in many sectors of economy, firms also produce undesirable outputs such as air pollution, solid waste and water effluents as by-products of their production process. A few decades ago these kinds of environmental impacts did not have a significant role for firms, but nowadays the state of affairs is completely different. This is because firms operate under more rigorous environmental legislation and thus, have to pay increasingly more attention to the environmental impacts of their activities. Under environmental regulation, undesirable outputs are not freely disposable, since the abatement and disposal of emissions creates costs for the producers, implying that regulation can have an effect on the performance of firms. Since the magnitude or even the direction of this effect is not clear, it is important to examine the impacts of regulation on performance and also follow how well the regulated firms perform over time. Also, without costly environmental regulation too much pollution would be emitted into the environment, and therefore, it is important to study how to reduce emissions in the most cost-effective way and what kind of regulation to use in a given economy or at a certain industry. This implies that we are not only interested in the effect of regulation on traditional performance measures, but also in its effect on the level of emissions and more comprehensive environmental indices and indicators. Thus, from a policy perspective, issues related to the environmental performance of production units are of great concern.

During the past three decades, the effects of environmental regulation on productivity or other performance measures such as competitiveness have been a topic for a number of studies both at the micro and macro level.[1] The general conclusion of these studies is mixed; according to some, regulation can decrease productivity notably (see e.g. Gray, 1987; Jorgenson and Wilcoxen, 1990), while the survey by Jaffe et al. (1995) concludes (by referring to a number of empirical studies) that the adverse effects of regulation on competitiveness have been small. In addition, a few studies have even suggested and/or demonstrated that environmental regulation can improve productivity and competitiveness, which is the so-called Porter hypothesis (Porter, 1991; Porter and van der Linde, 1995a,b). The rationale behind the Porter hypothesis is that firms do not always operate efficiently and that environmental regulation can lead firms to recognize and correct these inefficiencies. Since several empirical studies have demonstrated that the realized benefits from regulation are small for the regulated firms compared with the cost of environmental protection itself, most economists still remain quite sceptical about the Porter hypothesis (see Pizer and Kopp, 2005, for a discussion and references).

[1] See e.g. Christiansen and Tietenberg (1985) for an early survey of studies that examine the effects of environmental regulation on productivity and economic growth in the Unites States. For a more recent review, see Pizer and Kopp (2005).

Although the aforementioned studies examining the effects of environmental regulation on productivity or other performance measures are important, they do not explicitly consider the benefits of the reduced emissions. This means that from society's point of view they can overstate the adverse impacts of environmental regulation (Aiken and Pasurka, 2003). To account for this deficiency, a growing number of studies have developed environmentally sensitive productivity and efficiency measures that explicitly account for emissions and credit a producer for reducing them. In this literature, emissions are taken into account by constructing productivity and efficiency measures by modeling emissions typically either as weakly disposable outputs (see e.g. Färe et al., 1989; Färe et al., 2005) or as inputs (e.g. Koop, 1998; Reinhard et al., 1999). Many studies in this field also consider the effect of including emissions on productivity and efficiency (e.g. Yaisawarng and Klein, 1994; Weber and Domazlicky, 2001; Managi et al., 2004) or estimate shadow prices for the emissions (e.g. Färe et al., 1993, Coggins and Swinton, 1996; Färe et al., 2005).

The studies measuring and analyzing environmental sensitive productivity and efficiency are based on so-called production frontier methods. These techniques stem from the productivity and efficiency analysis literature and are frequently used in conventional performance measurement studies. This thesis concentrates on investigating how the production frontier methods can be used for measuring and analyzing environmental performance. By environmental performance measures, we refer to both environmental sensitive productivity and efficiency measures, as well as to other environmental performance indices and indicators that do not have a link to traditional productivity and efficiency measures. We note that it is important to define environmental performance measures in this broad sense, since most of the indices presented in the ecological and environmental economics literature lack a connection to production theory or to traditional productivity and efficiency measures. Many environmental performance measures based on production frontier methods, for their part, do not seem to have a proper ecological or environmental justification. Due to these aspects, it seems worthwhile to combine at least some ideas and tools proposed in different literatures when developing new approaches.

Both ecological and business economics literature have presented us with a large number of environmental performance measures.[2] However, most of these are oversimplified indicators such as "economic output per unit of waste" ratios that approach environmental performance from a very limited perspective. Some authors also propose to use a set of simple indicators to complement each other. Yet, this multiple-indicator approach ignores the fact that there are substitution possibilities between different emissions. Furthermore, it has also been common to use an arbitrary equal weighting scheme or weights based on subjective valuations for different environmental indicators. However, both of these approaches are obviously problematic, as the weighting lacks scientific reasoning. Thus, because of the aforementioned problems related to these approaches, it seems well-founded to rely on production frontier methods that do not require an arbitrary weighting scheme or price information and can account for various emissions as well as inputs and outputs. Moreover, an additional advantage of production frontier methods is their rigorous connection to microeconomic theory.

As stated earlier, while environmental performance measurement and analysis can be useful for firms or other production units, these are most typically relevant for society. To this end, there are at least three compelling reasons to measure environmental performance (see e.g. Lovell, 2005, for discussion). (1) Environmental performance measures track changes in living standards. By focusing only on market activities, performance measures can yield misleading signals concerning the changes in living standards, because also non-market activities such as environmental impacts are important for the overall welfare of society. (2) Improvements in environmental performance are necessary for sustainable development, which is defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. (3) There is a call for quantitative approaches that can be used as practical instruments in environmental policy analysis. In this respect, production frontier methods have a potential to inform and enhance public policy regarding the interactions between the economy and the environment.

[2] For surveys of various environmental performance measures and indicators based on frontier and non-frontier approaches, see e.g. Tyteca (1996), Olsthoorn et al. (2001) and Zhou et al. (2008).

## 2. Objectives of the study

The main objective of this thesis is to develop new quantitative approaches for environmental performance analysis based on production frontier methods. The general aim is to develop approaches that could avoid at least some of the deficiencies or limitations in the existing methods, and thus complement the tools of the performance measurement literature. The common theme for the new techniques proposed in Articles I-IV is that they utilize the ideas of the existing performance measurement techniques, but in comparison to these, also present extensions that can be particularly useful in various kinds of environmental applications. The ultimate ambition is to obtain comprehensive techniques that could support both management and incentive mechanisms and that could be used for the performance assessment of alternative policy instruments (compare e.g. Bogetoft, 2000; Zofio and Prieto, 2001; Bogetoft and Nielsen, 2003).

As, despite their potential, frontier methods are not yet widely used in the fields of environmental and ecological economics, one of the general objectives of the thesis is to employ the concepts and tools used frequently in these fields jointly with the frontier techniques. Related to this, it is important to notice that the measurement of environmental performance is of interest both in the productivity and efficiency analysis literature as well as in ecological economics. Nonetheless, so far these two literatures have been quite far apart, and have used different methodologies for environmental performance analysis. Thus, in the first article of the thesis, we propose a new approach for dynamic environmental performance analysis utilizing insights from both fields. The aim is to integrate some perspectives of ecological economics and the frontier approach of environmental performance assessment into a unified framework. In order to illustrate the possibilities and advantages of the presented methodology, we apply it to the dynamic environmental performance analysis of 20 member states of the European Union in 1990–2003.

In Articles II and III, our objective is to present two new application areas for production frontier methods: (1) eco-efficiency analysis of consumer durables, and (2) environmental cost-benefit analysis of competitive projects or plans. Both topics are strongly connected to the ecological and environmental economics literature as well as to environmental policy issues. The aim is not just to apply the existing frontier approaches to these areas, but to develop new techniques that can yield information about the relative performance of competitive products and projects measured in some currency unit. For this purpose, we propose new technical solutions that allow us to measure environmental performance in terms of absolute shadow prices. Although absolute shadow prices do not estimate the true prices of emissions or environmental impacts, they can be more useful to policy makers than the traditionally used relative shadow prices, as the former are easier to interpret. To illustrate the possibilities of the new approaches, Article II applies the absolute shadow price approach to the environmental performance evaluation of Sport Utility Vehicles, while Article III uses a numerical example of a household's car investment.

A common feature in the first three articles is that they all utilize a nonparametric frontier technique called data envelopment analysis (DEA). This implies that the approaches developed in these papers are nonparametric in the sense that no parametric assumptions are required for the environmental performance measurement. Although these approaches are very general with respect to assumptions about functional form, their common disadvantage is that they do not account for data noise. In addition, similarly with other nonparametric methods, they can be sensitive to the so-called "curse of dimensionality problem", which means that the convergence rate of the method deteriorates for high-dimensional problems. In Article IV, our goal is to develop a new semiparametric frontier approach that can avoid the curse of dimensionality problem and account for noise. Similarly to DEA, we estimate a semiparametric frontier under certain shape constraints (monotonicity, concavity) from the production theory. We elaborate a new estimation technique and show how our approach can be used to estimate technologies that generate pollution. We present an empirical application to the environmentally adjusted performance evaluation of U.S. coal-fired electric power plants. Interestingly enough, to our knowledge there have not been any previous studies that would have applied semiparametric stochastic frontier techniques to the estimation of pollution generating technologies or environmental performance.

# 3. Methodologies

## 3.1. Technical efficiency measures

All the articles in the thesis employ production frontier methods for measuring and analysing environmental performance. The foundation of frontier methods lies in production theory, and the methods are generally used to estimate various technical efficiency measures. Furthermore, most environmental performance measures based on frontier methods are closely linked to technical efficiency measures. Due to these reasons, we start this review section with a brief introduction to technical efficiency measures. The purpose of this subsection is to present the main ideas verbally, avoiding the use of any formulas. We follow this same strategy also in the following sections, which review other methodologies and related methods utilized in this thesis at a general level.[3]

In the seminal paper: “The Measurement of Productive Efficiency”, Farrell (1957) developed the standard methodology for efficiency measurement. In contrast to previous literature on production function, his insight was to allow the possibility of inefficient operations, immediately pointing to a concept of production frontier function as the benchmark. He concentrated on two issues at the micro level: (1) how to define efficiency and productivity, and (2) how to calculate the benchmark technology and efficiency measures. Importantly, the efficiency concepts that Farrell presented are still the basic definitions in use. In his presentation, overall efficiency of a firm[4] consists of two components: (i) technical efficiency, which reflects the ability of a firm to obtain maximum output from a given set of inputs, and (ii) allocative efficiency, which reflects the ability of a firm to use inputs in optimal proportions, given their respective prices. Later, overall efficiency has been called cost efficiency (or economic efficiency), but the concepts technical and allocative efficiency are still used in the same meaning.

[3] Note that we have chosen to avoid the use of formulas and figures in Section 3 by design. This does not only improve the readability of the text, but also makes it possible to keep the presentation relatively short, as we do not have to explain the meaning of various formulas and symbols. Moreover, we think it would not be reasonable to present an extensive review here, as there are many recognized review articles and books about the methodologies presented in this section. For a comprehensive and up-to-date introduction and review, we refer to Fried et al. (2008).

[4] Hereafter, by ”firm” we refer to production units in general, without discriminating between private enterprises and other types of production organizations such as public sector firms and non-for-profit firms.

Farrell originally considered technical efficiency in input orientation, and defined an input-oriented technical efficiency measure, which is similar to a capacity utilization measure of Debreu (1951).[5] Farrell's input oriented measure of technical efficiency is defined as a proportional scale down of all inputs at the given output level, subject to the condition that downsized inputs must still be able to produce the original output. According to this efficiency measure, a firm is said to be technically efficient, if it is not possible to reduce inputs proportionally without decreasing any of the outputs. Similarly, the Farrell output oriented measure of technical efficiency is defined as a proportional expansion of outputs at the given input level so that the scaled output is technically possible to produce.[6]

As can be observed from the above definitions, the Farrell efficiency measures are radial, since they either contract inputs radially keeping input ratios fixed or expand outputs radially keeping output ratios fixed. Related to this, Färe (1975) pointed out that Farrell's input and output oriented technical efficiency measures are mathematically equivalent to input and output distance functions introduced to economics by Shepard (1953, 1970). More specifically, the input and output distance functions are reciprocals to the Farrell efficiency measures. This link was actually overlooked by Farrell, even though Shepard's input distance function linked in the axiomatic production theory would have been an appropriate motivation for his choice of the radial contraction (or expansion). Later, this connection has been considered one of the most important benefits of the Farrell efficiency measures and has been utilized in many different contexts and applications. One important benefit of this connection, being utilized in this study as well, is that the Malmquist productivity index (see Section 3.4) can be defined either using distance functions or Farrell's efficiency measures. In general, the theoretical underpinnings of the Farrell efficiency measures have been developed by many authors (see e.g. Russell, 1990).

Although radial efficiency measures have some nice properties and are commonly used in empirical applications, these measures are not the only ones to measure technical efficiency. Starting from studies by Färe (1975), Färe and Lovell (1978), Kopp (1981) and Zieschang (1984), a large number of alternative nonradial efficiency measures have been presented in

[5] Because of this, some authors prefer to call it the Debreu-Farrell technical efficiency measure.
[6] As noted, Farrell did not derive the output oriented measure of technical efficiency in the paper, but concentrated only on the input oriented measure. However, since the output measure is based on a similar idea, both are typically called the Farrell efficiency measures.

the literature. The common idea of nonradial efficiency measures is that they do not adjust inputs or outputs proportionally in the same rate, but either use different adjustment factors for different variables or adjust only a part of the inputs or outputs, respectively. For example, following Kopp (1981), one can measure input-specific technical efficiency by scaling down one input and keeping other inputs and outputs at the same level. It is important to note that various nonradial efficiency measures have been particularly popular in environmental performance analysis.

Related to both radial and nonradial efficiency measures, Chambers et al. (1996, 1998) presented the directional distance function as a general representation of a technology. Notably, the general directional distance function encompasses almost all efficiency and distance measures presented in the literature as special cases, including the Farrell input and output measures as well as most nonradial efficiency measures. In the directional distance framework, alternative efficiency measures can be obtained by choosing the directional vector in a specific way. However, although the directional distance function is a very general representation, it always requires one to specify the direction vector a *priori*. This can be somewhat problematic in applications, as one does not necessarily have any guidelines on which direction(s) to prefer. In any case, the directional distance function has been employed in a number of empirical studies, including also many environmental performance applications.

It is important to note that efficiency measures introduced in the articles of the thesis are linked to technical efficiency measures presented in this section. First of all, in Article I we present a relative eco-efficiency measure that is mathematically similar to the Farrell input oriented efficiency measure. However, the conceptual difference to Farrell technical efficiency is that our eco-efficiency index uses value added and environmental pressures instead of traditional inputs and outputs. Articles II and III present new nonradial efficiency measures that are connected to the directional distance function, but cannot be obtained as special cases of it. Finally, Article IV measures inefficiency by using output orientation. The paper applies both additive efficiency and the Farrell technical efficiency measure and uses the latter in the empirical application.

## 3.2. Data envelopment analysis

In the previous subsection, we presented alternative efficiency measures by assuming that the theoretical optimum or efficient production frontier is known. In practice, it is very difficult, if not impossible, to construct an efficient production function without any empirical data. In fact, perhaps the most important contribution of Farrell (1957) was to discover and show that the production frontier function can be estimated from empirical data by using observations of the inputs and outputs from a number of firms. Farrell was also the first to estimate a piecewise linear frontier function (or technology) in nonparametric fashion without specifying any parametric functional form on frontier (like Cobb-Douglas). He concentrated on the single-output, multiple-input technology, assuming constant return to scale. The next important study within this nonparametric framework was Afriat (1972), which formulated the model with variable returns to scale in the case of one output.

Although both Farrell (1957) and Afriat (1972) made an important contribution to the nonparametric framework of piecewise linear frontier functions, the success of the nonparametric approach to efficiency measurement is mainly due to the influential paper "Measuring the Efficiency of Decision Making Units" by Charnes, Cooper and Rhodes (1978).[7] They extended Farrell's approach to multiple input, multiple output technologies, and referred to the mathematical programming method of measuring technical efficiency as "data envelopment analysis", with the acronym DEA. This term has established its place in the literature, and is now widely used. In addition to the generalization to multiple output technologies, another notable contribution of Charnes et al. (1978) was the explicit connection they derived between a productivity index, in the form of a weighted sum of outputs on a weighted sum of inputs, and the Farrell technical efficiency measure (in the case of constant returns to scale). In contrast to previous attempts, their model was also readily computable by using standard linear programming procedures. While Charnes et al. (1978) used the linear programming approach to estimate the DEA model under the assumption of constant return to scale, later Färe et al. (1983) and Banker et al. (1984) presented an extension to the variable returns to scale technology. These papers have led to

[7] For a detailed account of the early history of the nonparametric approach, see Førsund and Sarafoglou (2002, 2005).

a large literature on DEA and nonparametric efficiency analysis, consisting of more than one thousand application and methodological studies mainly in the fields of economics and operations research.[8]

Besides an efficiency measurement tool, DEA is generally regarded as a production frontier estimation method. Note that DEA truly envelops the data by assuming that all observations are inside the "true" production technology. However, this implies that DEA does not make any accommodation for noise, but interprets the whole deviation from the frontier as inefficiency. Because of the exclusion of noise, DEA is a deterministic estimation method. On the other hand, in contrast to the alternative stochastic frontier approach based on regression techniques (and presented in the next subsection), DEA does not require any assumptions about the functional form of the production technology or technical inefficiency. Neither does it put a constraint on the correlation structure between inefficiency and inputs and outputs, contrary to most regression based approaches. As DEA does not depend on any parametric assumptions, it is called the nonparametric approach to efficiency analysis.

From a practitioner's point of view, one of the most attractive features of DEA has been its ability to deal with multiple output technologies. In fact, the competitive parametric approaches were for a long time limited to the case of single output technologies only, or alternatively dual cost functions had to be used in the case of multiple outputs. Nowadays, there are also methods available to estimate multiple output production technologies within an econometric framework. However, in these distance function based methods one needs to make some normalization in order to obtain a dependent variable for the regression estimation. Since the estimation results can be sensitive to the chosen normalization, DEA remains an attractive method for applications, where there are multiple outputs but no price information. These include various public sector as well as environmental performance applications, among others.

In this thesis, we utilize DEA in developing new quantitative approaches for environmental performance measurement and analysis of comparable production units. DEA is the main

[8] DEA is particularly popular in operations research. As a great indication of this, Charnes et al. (1978) is nowadays one of the most cited papers in the field.

methodology for the first three articles. These papers present linear programming models (or formulations) that can be used in empirical applications to calculate relative performance scores. While Article I uses a DEA model that is mathematically similar to the model by Charnes et al. (1978), Articles II and III develop new models that have not been previously used in any performance measurement applications. However, as we discuss later, these new models are yet closely linked to certain previously presented DEA approaches.

### 3.3. Stochastic frontier analysis

In this subsection, we take a brief look at the econometric approach to efficiency measurement, which has as long a history as DEA. Interestingly, Farrell's influential study also launched an empirical literature on the parametric estimation of the production frontier. Within the parametric framework, the first approach to efficiency measurement was suggested by Aigner and Chu (1968), who assumed a Cobb-Douglas functional form for the production frontier function. Although the nonparametric approach of Farrell was dropped, they kept the mathematical programming format by calculating the unknown parameters by using linear and quadratic programming techniques. However, analogously with DEA, this parametric programming approach is deterministic in the sense that statistical noise is not accounted for. Afriat (1972) and Richmond (1974) developed the parametric approach further by presenting a statistical foundation on frontier estimation and an estimation technique based on ordinary least squares (called corrected ordinary least squares, COLS), respectively. However, also these approaches concentrated on the parametric estimation of a deterministic model that did not involve the noise term.

Aigner et al. (1977) and Meeusen and van den Broeck (1977) simultaneously developed a stochastic production frontier model that extended the previous parametric approaches by incorporating a statistical noise term in the analysis.[9] The stochastic frontier model consists of the deterministic production frontier, which is represented by some parametric function (such as Cobb-Douglas), and the composed error term. In contrast to deterministic approaches, the (composed) error term has two parts, a symmetrically distributed stochastic

[9] Battese and Corra (1977) is the third article often mentioned to initiate this research stream in the same year. However, as pointed out in Førsund and Sarafoglou (2002), Battese and Corra (1977) is not a parallel discovery, since it already refers to Aigner et al. (1977).

component, representing statistical noise, and a stochastic component with a one-sided distribution, representing inefficiency. Similarly to the usual regression models, it is thought that statistical noise arises from the omission of relevant variables, as well as from measurement errors and approximation errors associated with the choice of functional form for the deterministic production function.

In contrast to DEA and other deterministic approaches, the main benefit of SFA is clearly its stochastic character. However, although the stochastic frontier approach can incorporate a statistical noise term into the efficiency analysis, it is not without downsides. In fact, in order to estimate the model and disentangle inefficiency from noise, strong parametric assumptions are generally needed. To estimate the proposed SFA model, Aigner et al. (1977) and Meeusen and van den Broeck (1977) had to specify a functional form for the deterministic production frontier as well as to make distributional assumptions for inefficiency (half-normal/exponential) and noise (normal). Moreover, they assumed that inefficiency and noise are statistically independent of each other as well as of inputs. Based on these assumptions, it was then shown that the model can be estimated consistently by using either maximum likelihood or a technique called modified ordinary least squares (MOLS).

After the seminal papers on SFA, a large literature on stochastic frontier estimation has arisen. The original model used for production frontier estimation has been adapted to other contexts, including cost and profit frontiers as well as distance function estimation. In addition, there have been many extensions that relax one or several assumptions used in the original model. For example, more general distributions have been specified for inefficiency than the originally proposed half-normal and exponential distributions. In addition, the basic cross-sectional framework has been extended to a panel data setting, which allows one to relax some of the strong distributional assumptions necessary in the cross-sectional setting.

For a long time, it was thought that SFA is a purely parametric method, without any links to the nonparametric DEA approach. Recently, various semi- and nonparametric stochastic frontier models have been developed both to relax some of the restrictive assumptions used in the fully parametric stochastic frontier models and to narrow the gap between SFA and DEA.

However, most semi- and nonparametric SFA approaches presented in the literature are based on kernel regression or other nonparametric smoothing techniques, which use different assumptions as DEA. Instead of a piecewise linear frontier, these approaches assume a smooth (i.e. differentiable) frontier and require one to specify a value for the smoothing parameter, which is not required in DEA or in parametric SFA.

To bridge the gap between stochastic frontier analysis (SFA) and data envelopment analysis (DEA), the recent paper by Kuosmanen and Kortelainen (2007) introduced a new encompassing framework for productive efficiency analysis, referred to as Stochastic Nonparametric Envelopment of Data (StoNED). Specifically, StoNED combines a nonparametric, piecewise linear DEA-like frontier with a stochastic SFA-like composite error term consisting of inefficiency and noise terms. Importantly, both DEA and SFA can be obtained as constrained special cases of the more general StoNED model. To estimate the StoNED model, Kuosmanen and Kortelainen employed a two-stage estimation strategy. In the first stage, the shape of the frontier is estimated nonparametrically by using convex nonparametric least squares (CNLS) regression (Hildreth, 1954; Kuosmanen, 2008), while the second stage employs estimation techniques adopted from the SFA literature.

In Article IV of the thesis, we concentrate on studying the estimation of semiparametric stochastic frontier functions. Our main objective is to extend the work of Kuosmanen and Kortelainen (2007) to semiparametric frontier functions by developing a new approach which allows us to impose shape constraints on the frontier function. Besides elaborating a new estimation technique, we show how our approach can be used to estimate technologies that generate pollution.

### 3.4. Malmquist index

Traditionally, production frontier methods have been employed in the estimation of various efficiency measures. However, during the last 15 years, they have also been used extensively in estimating changes in total factor productivity (TFP) and its components. Previous studies applying frontier methods to TFP measurement are mostly based on the Malmquist productivity index that was introduced as a theoretical index by Caves et al. (1982) and further developed and popularized as an empirical index by Färe et al. (1994a, 1994b). The are many reasons for the popularity of the Malmquist index, but one of the most important ones is its data requirements in comparison to other productivity indices traditionally used in TFP studies. To this end, it does not require price information or behavioral assumptions such as cost minimization, which implies that it can be used in situations where prices do not either exist or have little economic meaning. Perhaps even more importantly, the Malmquist productivity index can be decomposed into economically relevant sources of productivity change. Related to this, Färe et al. (1994a, 1994b) showed how the Malmquist productivity index can be expressed as the product of an efficiency change index and a technical change index, which measure the extent to which productivity changes are due to changes in efficiency and technology, respectively.[10]

Although the Malmquist index and its variations have mainly been employed in TFP studies, following the original proposition of Malmquist (1953), these indices can equally well be applied in other areas. In Article I of the thesis, we will utilize this insight by using the Malmquist index in constructing an environmental performance index (EPI). In addition, we adapt the decomposition of total factor productivity by Färe et al. (1994a, 1994b) to our application, by showing that the overall environmental performance index can be decomposed into environmental technical change and relative eco-efficiency change components.

### 3.5. Environmental performance measurement with frontier methods

In this section, we take a brief look at the studies that have applied frontier methods in the estimation of different environmental performance measures. Note that with environmental performance measures, as earlier, we refer to both environmental sensitive productivity and efficiency measures, as well as to other measures or indicators connected to environmental performance. We find it important to have a common terminology for these various performance measures, even though they would not always be equally sophisticated. By this choice of terminology, we follow the review article of Tyteca (1996).[11]

[10] However, note that Nishimizu and Page (1982) first identified technical change and efficiency change as two distinct components of productivity change.

[11] It is somewhat unfortunate that there is no established terminology in this literature, which is the reason why different terms are often used in the same meaning. Because of this deficiency, it is important to define the terms used (like environmental performance here).

Most typically, environmental performance applications based on frontier methods have basically just integrated emissions or undesirable outputs into the classical Farrell framework of efficiency analysis. In these studies, environmental production technology (or pollution generating technology) is defined by accounting for undesirable outputs in addition to traditional inputs and outputs. The usual approach is to measure the environmental performance of the firm as distance to the environmental technology. However, there are many different ways to measure the distance to the frontier (or technology). Some authors have preferred to adjust undesirable outputs, keeping good outputs and inputs at the same level; others have reduced emissions and inputs simultaneously, keeping good outputs constant. Also simultaneous changes in all variables have been used, by means of the directional distance function and the so-called hyperbolic measure. Note that the choice of efficiency measure (or distance) is linked to the objective functions pursued by the organizations under study as well as to the purpose of the application. In environmental performance analysis, the choice of efficiency measure is generally guided by organizational goals (defined by private interests) or by those of public policy.

To estimate environmental performance measures from empirical data, one needs to decide which frontier method to use for the estimation. In this field, empirical frontier applications have mainly been based on DEA, deterministic parametric programming (Aigner and Chu, 1968) and parametric SFA methods. However, a large number of the earlier studies have used DEA-based models. Evidently, the most difficult question in estimating frontier functions and/or efficiency measures in this context has been the issue of how to model emissions. In fact, although various approaches have been given justification and many academic debates have emerged, it is still open to discussion which is the “correct way” to model emissions when estimating environmental production technologies.

In the DEA literature, many studies have modeled emissions as weakly disposable outputs (including a seminal paper by Färe et al., 1989), which means that the model accounts for the possibility that emissions cannot be reduced freely or without costs. Studies that use parametric programming have usually modeled or tried to model emissions as weakly disposable (see e.g. Färe et al. 1993, 2005). Instead, in the classical and Bayesian SFA literature it has been common to model emissions as inputs (e.g. Koop, 1998; Reinhard et al. 1999; Managi et al., 2006). This “input approach” originates from the environmental economics literature, where the standard approach of modeling nonlinear production and abatement processes is to treat waste emissions “simply as another factor of production” (Cropper and Oates, 1992). One practical reason to treat emissions as inputs has also been the fact that it is considerably easier to treat emissions as explaining variables rather than dependent ones in regression models.

In addition to modeling emissions as inputs or weakly disposable outputs, several other approaches have been presented. Perhaps the most common of these has been to model emissions as normal outputs after data transformation; see e.g. Scheel (2001) and Korhonen and Luptacik (2004) for DEA models and Fernandez et al. (2005) for a SFA model, respectively. Recently, Coelli et al. (2007) presented an interesting DEA approach, which incorporates a material balance condition into the frontier model. Further, some studies have recently used a DEA-like model to aggregate various sustainability and/or environmental indicators into a composite indicator. This weighting approach, also called “the benefit of the doubt weighting”, does not consider traditional inputs and outputs, and in that sense, differs from the traditional DEA approaches. For applications of this approach, see e.g. Cherchye and Kuosmanen (2006) and Zhou et al. (2007).

In this thesis, Article I adapts the benefit of the doubt weighting scheme to environmental performance analysis, and uses it along with the Malmquist index approach. In Articles II and III, we elaborate the absolute shadow price approach, which differs from other approaches presented in the literature, but has some similarities with the data transformation approach mentioned above. In contrast, in Article IV we follow the standard environmental economics and SFA approaches by modeling emissions as inputs.

## 4. Summary of the articles

The dissertation consists of four articles, all of which contribute to the subject of environmental performance analysis from slightly different perspectives. The main objective of all these articles was to develop new quantitative approaches for analyzing the environmental performance of comparable production units. This was done by utilizing both data envelopment analysis (DEA) and stochastic frontier analysis (SFA), the two most widely used production frontier methods in today's literature. The purpose was to improve the existing performance measurement tools by establishing new methods that would employ insights from the ecological and environmental economics literature jointly with frontier techniques, but also avoid some of the limitations in the current frontier approaches. Thus, the contribution of the articles is mainly methodological, although empirical applications are also presented. Next I take a brief look at the articles. The purpose is to present the main contribution and results of each paper, and to underline the most interesting aspects to the theme of this thesis.

**Article I:** Kortelainen, M. (2008): Dynamic Environmental Performance Analysis: A Malmquist Index Approach. *Ecological Economics* 64(4), 701-715.

The objective of this article was to develop a general framework for dynamic environmental performance analysis by utilizing insights from both productive and efficiency analysis as well as ecological economics literature. The background to the problem lies in the earlier paper by Kuosmanen and Kortelainen (2005), who presented a general approach to relative eco-efficiency measurement based on DEA. However, as their approach cannot account for technical change or explain changes in environmental performance over time, it can primarily be used for environmental performance analysis in a static setting. The aim of Article I was to generalize this static approach to a dynamic setting.

For constructing a new framework for the dynamic environmental performance analysis, we utilized frontier techniques and a Malmquist index approach. Although the Malmquist index has been utilized in a great number of studies, most of them have used it for measuring changes in total factor productivity and its components. However, in this study we used the Malmquist index approach to construct an environmental performance index (EPI), not a total factor productivity index. In contrast to most other environmental performance measures based on frontier techniques, the proposed environmental index has strong links to ecological economics literature. There are two reasons for this. (1) First of all, our environmental performance measure builds on the standard definition of eco-efficiency as it is presented in ecological economics. Thus, although we use a Farrell efficiency measure to calculate relative eco-efficiency scores, we measure performance in terms of value added and environmental pressures instead of traditional inputs and outputs. In other words, inputs and outputs are not used as model data, although they can implicitly affect either the numerator or the denominator of the eco-efficiency ratio. Related to this orientation, we also approach environmental performance assessment from a more aggregated perspective than is typically done in productivity and efficiency analysis. (2) Second, in constructing aggregated environmental variables we utilized environmental impact assessment methods that are often used in the applications of ecological economics and industrial ecology, but not in frontier applications. In comparison to DEA-based environmental performance approaches that use pollutants as model variables, our approach has better discriminatory power because of the aggregated environmental variables. This can be relevant in empirical applications, as our approach can enable one to include a larger number of pollutants in the analysis without losing the discriminatory power of the technique.

Since it is generally important to recognize the sources of environmental performance changes, we presented a decomposition for our environmental performance index, which is technically analogous to the frequently used Malmquist index decomposition. Besides decomposing changes in overall environmental performance into changes in relative eco-efficiency and shifts in environmental technology, we decomposed the latter component further into a magnitude index and a component that we call environmental bias index. It is worth emphasizing that these different components of the environmental performance index can be highly useful when analyzing the sources and reasons for changes in environmental performance over time.

The proposed technique was applied at the macro level to a dynamic environmental performance analysis of 20 member states of the European Union in 1990-2003. The main purpose of this application was to examine how changes in environmental performance and its components have developed during the sample period in general, identify the major factors in each country’s performance, and illustrate the possibilities and advantages of the presented methodology. Recognizing the possibility to incorporate many pollutants into the analysis, we calculated an environmental performance index and its components for the sample countries accounting for 12 different air pollutants. According to the country-level results, environmental technical progress proved to be the key factor behind the improvement in the overall environmental performance, whereas changes in relative eco-efficiency had been minor for most countries during the sample period. Further decomposition of the environmental technical change revealed that the bias effect had been negligible during the period studied.

**Article II:** Kortelainen, M. and T. Kuosmanen (2007): Eco-Efficiency Analysis of Consumer Durables Using Absolute Shadow Prices. *Journal of Productivity Analysis* 28(1-2), 57-69.

The aim of this article was to develop a general method for the environmental performance analysis of consumer durables based on DEA. In contrast to previous studies evaluating products or consumer durables with frontier methods (see e.g. Kamakura et al., 1988; Papahristodoulou, 1997; Fernandez-Castro and Smith, 2002; Chumpitaz et al., 2008), we considered the measurement problem from a policy maker's perspective. This is a natural choice in environmental performance evaluation, since consumers do not necessarily care about the environmental impacts of the products they consume. This viewpoint also led us to propose some novel technical solutions for environmental performance analysis.

Perhaps the most relevant innovation of the article was to measure performance in terms of absolute shadow prices that are optimized endogenously within the model to maximize the eco-efficiency of the product. In contrast to the usual relative weights used in DEA, in our approach the shadow prices are anchored in some currency unit. One relevant advantage of using absolute rather than relative shadow prices is that the efficiency measure has a direct economic interpretation as a monetary loss due to inefficiency, expressed in money. The interpretation of shadow prices also becomes more obvious, as one can connect them to prices observed in real markets. One additional advantage of absolute shadow prices is that they enable one to impose absolute price restrictions that cannot be employed in the usual DEA models (see e.g. Dyson et al., 2001, for a discussion on this). In particular, for policy makers the absolute price restrictions can be more accessible and transparent than relative restrictions, since lower and upper bounds have a more intuitive interpretation.

To illustrate the relative benefits of our approach, we compared it both technically and empirically to more traditional DEA models based on relative shadow prices. We applied the proposed technique to the eco-efficiency evaluation of Sport Utility Vehicles (SUVs) using a data set from the Finnish Vehicle Administration (AKE). This data set included the total of 88 different models, from which 49 were gasoline engine and 39 diesel engine vehicles. In order to demonstrate the usefulness of the approach in environmental policy evaluation, we examined the differences in environmental performance between gasoline and diesel vehicles. To eliminate other possible effects (such as safety and comfort features), we considered the subset of SUV models available both with a gasoline and diesel engine. The comparison included 18 pairs of models with (almost) identical features, expect for engine type. According to the results, only in one case a gasoline vehicle performed better than a corresponding diesel engine vehicle. More importantly, there were remarkable differences in certain pairs and the average difference between gasoline and diesel engine was also relatively high: the gasoline vehicles generated about 1.1 euros higher costs per 100 km than their diesel engine counterparts. Thus, these results strongly seem to suggest that at least in Finland diesel engine SUVs are more environmentally friendly than the gasoline engine SUVs. Above all, the application shows that this kind of analysis could be generally used for assessing whether the use of diesel vehicles should be encouraged by the government, and in designing efficient policy instruments.

**Article III:** Kuosmanen, T. and M. Kortelainen (2007): Valuing Environmental Factors in Cost-Benefit Analysis Using Data Envelopment Analysis. *Ecological Economics* 62(1), 56-65.

In this article, the purpose was to study how to apply DEA for environmental valuation within environmental cost benefit analysis (ECBA), which is one of the most important practical tools in environmental economics. In general, ECBA is widely applied for the social evaluation of investment projects and policies, and in many countries legislation requires ECBA to be implemented for all public projects and policies that have significant environmental impacts. Despite its popularity, there are many methodological problems related to its application. One of the most heavily debated stages of ECBA is clearly the economic valuation of environmental impacts due to shortcomings and problems in the conventionally used valuation techniques.

The main contribution of the article was to extend the environmental valuation methodology used in ECBA by developing a new method, which would not require price estimation for environmental impacts. Instead of using conventionally applied stated or revealed preference methods, we applied DEA-style shadow prices that are optimized endogenously within the model. However, as ECBA is based on prices anchored in some currency unit, one cannot employ relative shadow price multipliers used in traditional DEA for ECBA. Because of this shortcoming in traditional DEA, we showed how to modify DEA to this context by applying absolute shadow prices analogously with Article II. Thus, while conventional DEA models rely on relative efficiency measures and shadow prices, the presented approach uses absolute prices and measures profitability (or inefficiency) of competitive projects on an absolute scale in money. Even though our approach does not require the subjective valuation of environmental impacts, we showed that it is yet possible to include value judgements and other stated preference information into the model. This is particularly useful for sensitivity analysis, which has a major role in practical cost-benefit applications.

To illustrate the proposed approach with an application, we considered a numerical example, where an environmentally conscious household considers investment in a new vehicle. In this example with real-world data, we were able to cut down the number of economically rational alternatives from 88 to 2 and to choose the more robust of these two. However, as this is only an illustrative example, there is a need for full-scale empirical applications that would confirm the reliability of the proposed model. As far as the empirical applications are concerned, we are aware of one paper that has already applied our approach: Bosetti and Buscher (2005) use it to the comparative assessment of climate policies.

Finally, one should note that although both Article II and Article III employ absolute shadow prices for performance analysis, there are some differences between the approaches presented in these papers. First, in Article II we measure the environmental performance of consumer durables in terms of economic cost per a single use of the consumer durable, while in Article III the profitability of the projects is assessed in terms of the discounted net present value (NPV) of the economic benefits over the entire life-cycle of the project. Second, in Article III inefficiency scores (or comparative advantages) are allowed to be positive by measuring performance relative to the next best alternative, analogously with the super-efficiency approach by Andersen and Petersen (1993). The advantage of this super-efficiency approach is that one can find unique shadow prices also for the efficient projects. However, the well-known problem related to super-efficiency formulation is that it may not have solutions for some data sets.

**Article IV:** Kortelainen, M. (2008): Estimation of Semiparametric Stochastic Frontiers Under Shape Constraints with Application to Pollution Generating Technologies. MPRA Paper 9257, University Library of Munich, Germany.

The starting point for this article was to study semiparametric stochastic frontier estimation under shape constraints implied by microeconomic theory. The motivation for this work was the fact that most semi- and nonparametric stochastic frontier techniques presented in the literature do not allow one to impose any shape constraints (or regularity conditions) on the frontier function. Two exceptions to these studies are Banker and Maindiratta (1992) and Kuosmanen and Kortelainen (2007), which present two different approaches to the shape-constrained stochastic frontier estimation. Although the techniques presented in these papers are very general, they can be sensitive to "the curse of dimensionality problem". This problem, general in nonparametric regression methods, implies that when the data include several input variables (usually 3 or more) a very large sample is needed to obtain an acceptable estimation precision (see e.g. Yatchew, 2003, for a detailed discussion).

The main aim of Article IV was thus to broaden the stochastic frontier estimation by proposing a new semiparametric technique, which would avoid the curse of dimensionality problem, but would allow one to impose shape constraints on the frontier function. The semiparametric specification presented in the paper is based on the single-index model, which is one of the most popular semiparametric models in the econometrics literature. However, we are not aware of any previous studies, which would have used the model in this setting. As the single-index model does not require the specification of functional form for the production function *a priori*, it seems worthwhile to consider how this specification can be used in the stochastic frontier estimation in general and in the shape-restricted estimation, in particular.

We showed how the semiparametric single-index model can be estimated in three stages by using (1) single-index estimation techniques, (2) convex nonparametric least squares (CNLS) and (3) method of moments. While the first stage applies either sliced inverse regression or a monotone rank correlation estimator (both of which are common single-index estimation techniques), the second and third stages are based on similar estimation techniques as in the StoNED approach by Kuosmanen and Kortelainen (2007). Due to this connection, the proposed approach can be considered a semiparametric extension to StoNED.

The second contribution of the paper was to show how the proposed approach can be used for the estimation of environmental production technologies. Following the standard environmental economics and frontier approaches, we treated emissions as inputs when estimating environmental production function. We illustrated this input approach with an empirical application to the environmentally adjusted performance evaluation of U.S. electric power plants. We estimated environmental production frontiers and environmental efficiency scores by using the methods proposed in the paper and some traditional frontier methods, respectively. Interestingly enough, the results given by the proposed techniques differed from the results of traditional DEA and SFA. To our knowledge, this was the first study to apply semiparametric stochastic frontier techniques to the estimation of pollution generating technologies or environmental performance.

## 5. Concluding remarks

The main objective of this study was to develop new quantitative approaches for environmental performance analysis based on production frontier methods. The common theme for the four articles of the thesis is that they complement the existing performance measurement tools in productivity and efficiency literature by elaborating approaches that can be particularly useful in various kinds of environmental applications. In contrast to many other environmental measurement tools based on frontier methods, the new techniques employ the concepts and tools used frequently in the fields of environmental and ecological economics jointly with the frontier techniques.

Overall, we think that the new techniques proposed in the thesis provide both interesting insights and various application possibilities for the literature of environmental performance analysis. However, further research is yet needed to strengthen the applicability of the methods in other contexts. Following the applications in Articles II and IV, it would be important to empirically compare the new approaches with more traditional performance measurement tools. In particular, it would be of great concern to compare the DEA-based environmental valuation approach presented in Article III to the traditional revealed and stated preference valuation methods in a full-scale empirical application. In addition, we find it important to extend the study on the possibilities of the shape-constrained, semiparametric approach of Article IV by comparing it to alternative semiparametric stochastic frontier techniques presented in the literature.

One relevant area for future research would also be to study the use of stated and revealed preference information along with the nonparametric approaches presented in the first three articles. In fact, although the approaches proposed in these papers do not require any *a priori* information concerning the importance of different environmental pressures or impacts, some applications might offer additional information about the importance of different environmental problems. In principle, additional information could be included into DEA models quite easily by using weight constraints, but the challenge is how to impose constraints without using *ad hoc*, subjective bounds. In this respect, we believe that the traditional valuation methods used in environmental economics could provide more objective ways to impose additional information into the DEA-based environmental performance approaches.

Lastly, it needs to be emphasized that the new approaches developed in the thesis are not restricted to merely environmental applications, but can also be applied in other kinds of contexts. In fact, the absolute shadow price approach developed in Article II and III has already been modified and used in profit efficiency analysis (see Kuosmanen et al., 2005). In addition, the semiparametric estimation technique developed in Article IV can be employed in various kinds of applications that concentrate on technical efficiency analysis. It should also be quite straightforward to extend the shape-constrained semiparametric frontier approach to the estimation of cost and profit frontier functions. In fact, these would be rather natural application areas, since cost and profit functions have to satisfy certain shape-constraints implied by microeconomic theory.

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